THE NUCLEAR RETARC SULKY:

AN UPSIDE DOWN CRATER

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14. ABSTRACT
Sulky, an 85]ton nuclear cratering experiment, was detonated 90 ft below the surface in the dry basalt of Buckboard Mesa, Nevada Test Site on 18 December 1964 as part of the U.S. Plowshare Program. The resulting mound, called a retarc (crater spelt backward), was roughly symmetrical with an average radius of 100 ft, beyond which the ground surface was flexed and fractured for at least another 100 ft. The mound contained a central pit averaging 29 ft in radius and 21 ft high with the floor 9 ft above surface ground zero. The resulting measurements and analysis achieved the original objective of helping to define the nuclear rock cratering curve beyond optimum depth of burst. Viewed from the surface the Sulky mound appeared as a gjumbled pileh of basalt blocks sized by pre]existing joint surfaces. However, trenches cut through the mound revealed a well defined structure below the surface. Beginning in 1987 a new effort by DNA/AFWL/USGS mapped in detail the structure exposed by the trenches and individual basalt blocks on and beyond the mound. With good stratigraphic control provided by preshot corings, basalt layers were mapped across the mound showing upthrusting increasing inward until intersected by the central pit which is actually an gejection pith and the primary source of the jumbled blocks covering the mound surface. New analysis of the high]speed cinema followed the mound rise and then tracked many of the individual ejecta blocks exiting at high angles from the central portion of the mound, the gejection pith. Close correlation of these data provided an excellent benchmark for both centrifuge experiments and 2]D continuum and discrete element simulations which bounded the observables. Together the synthesis of all these efforts provided a dynamic link for better understanding the formation of the Sulky retarc and show just how close Sulky was to being a classical crater.

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ABSTRACT

Sulky, an 85-ton nuclear cratering experiment, was detonated 90 ft below the surface in the dry basalt of Buckboard Mesa, Nevada Test Site on 18 December 1964 as part of the U.S. Plowshare Program. The resulting mound, called a retarc (crater spelt backward), was roughly symmetrical with an average radius of 100 ft, beyond which the ground surface was flexed and fractured for at least another 100 ft. The mound contained a central pit averaging 29 ft in radius and 21 ft high with the floor 9 ft above surface ground zero. The resulting measurements and analysis achieved the original objective of helping to define the nuclear rock cratering curve beyond optimum depth of burst. Viewed from the surface the Sulky mound appeared as a "jumbled pile" of basalt blocks sized by pre-existing joint surfaces. However, trenches cut through the mound revealed a well defined structure below the surface. Beginning in 1987 a new effort by DNA/AFWL/USGS mapped in detail the structure exposed by the trenches and individual basalt blocks on and beyond the mound. With good stratigraphic control provided by preshot corings, basalt layers were mapped across the mound showing upthrusting increasing inward until intersected by the central pit which is actually an "ejection pit" and the primary source of the jumbled blocks covering the mound surface. New analysis of the high-speed cinema followed the mound rise and then tracked many of the individual ejecta blocks exiting at high angles from the central portion of the mound, the "ejection pit". Close correlation of these data provided an excellent benchmark for both centrifuge experiments and 2-D continuum and discrete element simulations which bounded the observables. Together the synthesis of all these efforts provided a dynamic link for better understanding the formation of the Sulky retarc and show just how close Sulky was to being a classical crater.

SULKY

NUCLEAR CRATERING EVENTS

[NORDYKE, 1976; MODIFIED]

Table 1. Summary of nuclear cratering explosions contributing data for nuclear excavation technology.

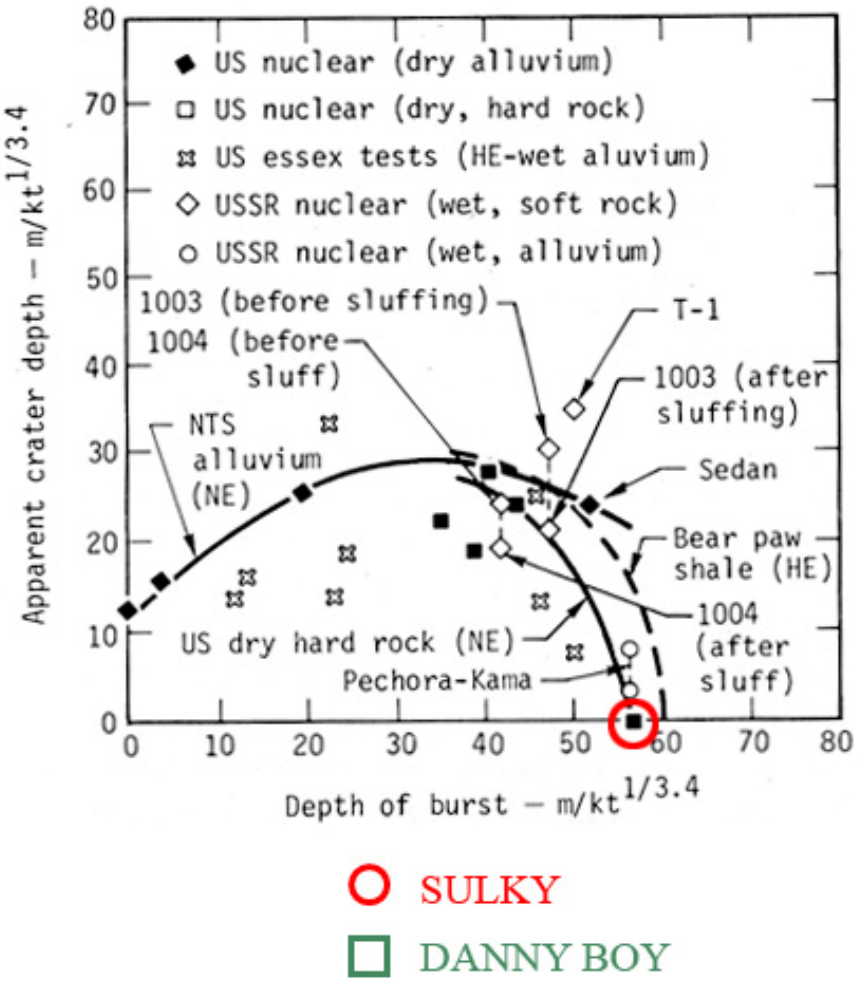
Name	Date	Configuration	Yield (kt)	Depth-of-burst (m)	Apparent crater radius (m)	Apparent crater depth (m)	Medium	Water conditions	Ref.
U.S. explosions									
Jangle S	1951	Single	1.2	1.1	14	6.4	Alluvium	Dry	Nordyke (1961)
Jangle U	1951	Single	1.2	5.2	40	16	Alluvium	Dry	Nordyke (1961)
Teapot ESS	1955	Single	1.2	20	45	27	Alluvium	Dry	Nordyke (1961)
Neptune	1958	Single (under slope)	0.115	31	31	11	Tuff	Dry	Shelton *et al.* (1960)
Danny Boy	1962	Single	0.42	34	33	19	Basalt	Dry (<1%)	Nordyke and Wray (1964)
Johnnie Boy	1962	Single	0.5	0.53	18	9.1	Alluvium	Dry	Nordyke (1964)
Sedan	1962	Single	100	194	184	98	Alluvium	Dry (~20%)	Nordyke and Williamson (1965)
Sulky	1962	Single	0.087	27	—	—	Basalt	Dry (<1%)	Videon (1965)
Palanquin	1965	Single	4.3	85	36	24	Rhyolite	Dry (<1%)	Videon (1966)
Cabriolet	1968	Single	2.6	52	54	37	Rhyolite	Dry (<1%)	Tewes (1968)
Buggy	1968	Row of 5	1.1	41 spacing: 46 m	76[b]	21	Basalt	Dry (<1%)	Tewes (1968)
Schooner	1968	Single		108	130	63		Wet (~10%) but unsaturated	Tewes (1970)
Soviet experience									
1003	—	Single	1.1	48	53.5 (62.0)[a]	31 (20)[a]	Siltstone	Saturated	Myasnikov *et al.* (1970)
1004	—	Single	~125	~178	204 (~157)[a]	100 (83)[a]	Sandstone/ shale	Saturated (12%)	Myasnikov *et al.* (1970)
T-1	—	Single	0.2	31.4	40	21	Sandstone	Saturated (12.8%)	Myasnikov *et al.* (1970)
T-2	—	Row of 3	0.2	31.4 spacing: 40 m	32.5[b]	16	Sandstone	Saturated (12.8%)	Myasnikov *et al.* (1970)
Pechora-Kama	1971	Row of 3	15	~127 spacing: ~165 m	150–170[b]	10–15	Alluvium	Saturated	Kireev *et al.* (1975)

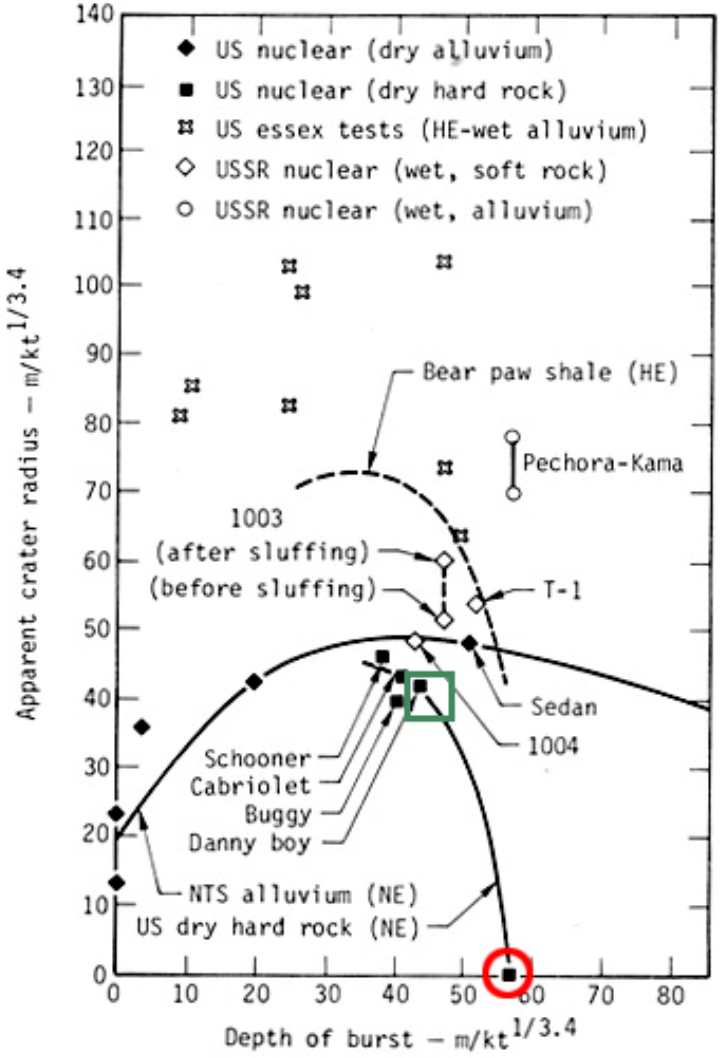
[a]After sluffing of side slopes.
[b]Average half-width of row crater.
[c]Includes 7.6% non-water gas-forming component.

SULKY

NUCLEAR CRATERING EVENTS

[NORDYKE, 1976; ANNOTATED





SULKY

BACKGROUND - 1

- THE SULKY NUCLEAR CRATERING EXPERIMENT WAS CONDUCTED UNDER THE AUSPICES OF THE U.S. ATOMIC ENERGY COMMISSION (AEC) AND DIRECTED BY THE LAWRENCE RADIATION LABORATORY (LRL) NOW THE LAWRENCE LIVERMORE NATIONAL LABORATORY (LLNL)
- SULKY WAS ONE OF A NUMBER OF PLOWSHARE CRATERING EXPERIMENTS FOR PEACEFUL USES OF NUCLEAR WEAPONS FOR EXCAVATION PURPOSES – ITS DEPTH OF BURST WAS SET TO EXAMINE EFFECTS NEAR OPTIMUM DEPTH OF BURST (DOB)
- THE PRIMARY OBJECTIVES WERE TO DETERMINE: 1) THE DISTRIBUTION OF SURFACE RADIOACTIVITY, 2) THE DISTRIBUTION OF AIRBORNE RADIONUCLIDES AND 3) CRATER SIZE, MECHANISMS AND RESULTING BLAST-INDUCED MATERIAL PROPERTY CHANGES
- CRATERING AND RELATED EFFECTS PROJECTS WERE CONDUCTED BY THE U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION (WES) AND THE U.S. ARMY CORPS OF ENGINEERS NUCLEAR CRATERING GROUP (NCG) AND THEIR CONTRACTORS
- THE SULKY SITE WAS CHOSEN BASED ON PREVIOUS EXTENSIVE STUDY OF THE GEOLOGY, MATERIAL PROPERTIES AND CRATERING OF THE BASALT AT BUCKBOARD MESA, NEVADA TEST SITE BEGINNING WITH THE 1960 BUCKBOARD MESA HE EVENTS (3 20-TON AND 5 1/2-TON; VORTMAN, 1962), THEN 1962 DANNY BOY (.42 KT NE; NORDYKE, 1963), THEN 1964 PRE SCHOONER I EVENTS (4 20-TON HE; SPURILL, 1965) AND FINALLY 1964 DUGOUT (5 20-TON HE ROW; SPRUILL, 1965)
- FOLLOWING THE SULKY EVENT THE 1968 BUGGY EVENT (5 1-KT NE ROW; LESSLER, 1968) WAS CONDUCTED SOME 7 MILES SOUTH IN A SIMILAR BASALT MEDIA

SULKY

BACKGROUND - 2

- DURING THIS TIME PERIOD VARIOUS GEOPHYSICAL SURVEYS WERE CONDUCTED AND OVER 40 CORINGS WERE MADE TO DEFINE THE STRATIGRAPHY AND MATERIAL PROPERTIES OF EACH TEST SITE, INCLUDING POSTTEST CORINGS OF EACH OF THE CRATERS, (BANKS, 1964)
- FOR SULKY, 9 CORINGS WERE ANALYZED PRETEST PLUS THE 36-IN. CALYX CORE FROM THE EMPLACEMENT HOLE AND 3 POSTTEST CORINGS WERE ANALYZED TO DEFINE THE CAVITY AND BLAST INDUCED MATERIAL PROPERTY CHANGES
- SULKY TOGETHER WITH THE EARLIER NE AND HE DATA HELPED TO DEFINE THE BASALT CRATERING CURVE FROM SURFACE TO BELOW OPTIMUM DEPTH OF BURST
- BEGINNING IN 1987 A NEW EFFORT TO MORE FULLY UNDERSTAND THE SULKY CRATERING MECHANISIMS, THE BASIS FOR THIS PAPER, WAS FUNDED BY DEFENSE NUCLEAR AGENCY (DNA) AND CONDUCTED BY THE AIR FORCE WEAPONS LABORATORY (AFWL) AND THE FLAGSTAFF OFFICE OF THE U.S. GEOLOGICAL SURVEY (USGS), ASSISTED BY SEVERAL CONTRACTORS: CALIFORNIA RESEARCH AND TECHNOLOGY (CRT), NEW MEXICO ENGINEERING RESEARCH INSTITUTE (NMERI), RESEARCH AND DEVELOPMENT ASSOCIATES (RDA) AND THE BOEING COMPANY (TBC)
- THIS EFFORT SUCCESSIVELY INTEGRATED PREVIOUS WORK WITH NEW FIELD MAPPING AND ANALYSIS OF THE EVENT CINEMA, IMPROVED 2-D CONTINUUM AND DISCRETE ELEMENT CALCULATIONS AND CENTRIFUGE EXPERIMENTS ALL TO PROVIDE AN IMPROVED UNDERSTANDING OF THE SULKY CRATERING MECHANISIMS

SULKY

EVENT INFORMATION

[VIDEON, 1965; LUTTON, 1966; HENNY, 1990]

- **OPERATION:** WHETSTONE/PLOWSHARE PROGRAM
- **EVENT:** SULKY
- **EVENT DIRECTORS:** LRL UNDER THE AUSPICES OF THE AEC
- **DEVICE:** PLOWSHARE
- **YIELD:** 85 +/- 15 TONS NE (0.085 KT)
- **DETONATION TIME:** 18 DECEMBER 1964 @ 1135 PST (1935 GMT)
- **DOB:** 90 FT; 36-IN EMPLACEMENT HOLE, STEMMED WITH A CAL-SEAL PLUG, THEN PEA GRAVEL TO THE SURFACE
- **LOCATION:** NEVADA TEST SITE, AREA 18, BUCKBOARD MESA
- **EMPLACEMENT HOLE:** U18d
- **NEVADA STATE COORDINATES:** N 849,239.07; E 594,540.73
- **GEODETIC COORDINATES:** 37°04’57.7640” N, 116°20’33.2075” W
- **SURFACE ELEVATION:** 5,328.93 FT
- **WEATHER:** WINDS 8 TO 15 KNOTS FROM SSE
- **GEOLOGY:** HORIZONTALLY LAYERED BASALT: UPPER VESICULAR ZONE TO 60 FT, DENSE ZONE TO 130 FT - ALL OVERLAIN BY 1 – 3 FT SOIL; WATER TABLE BELOW 775 FT

SULKY

EVENT INFORMATION (Continued)

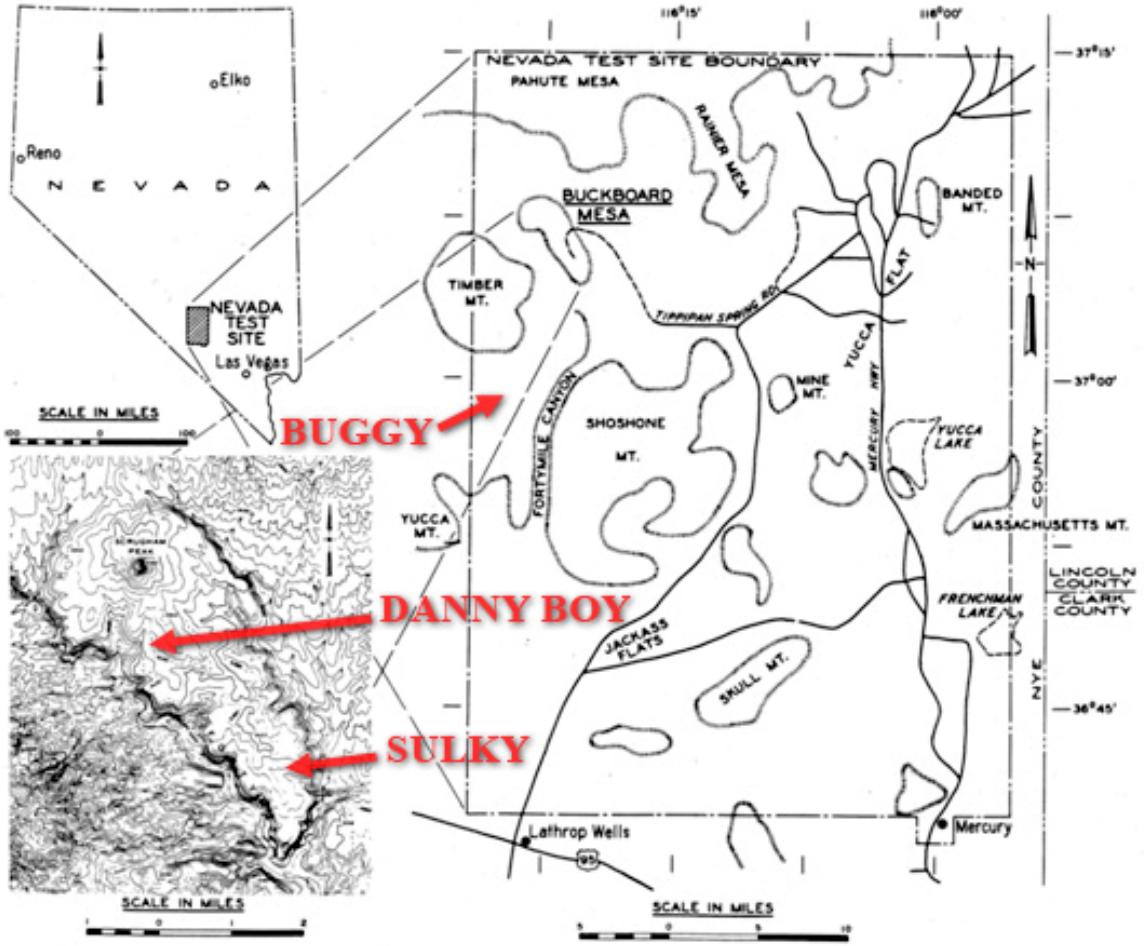
[VIDEON, 1965; LUTTON, 1966; HENNY, 1990]

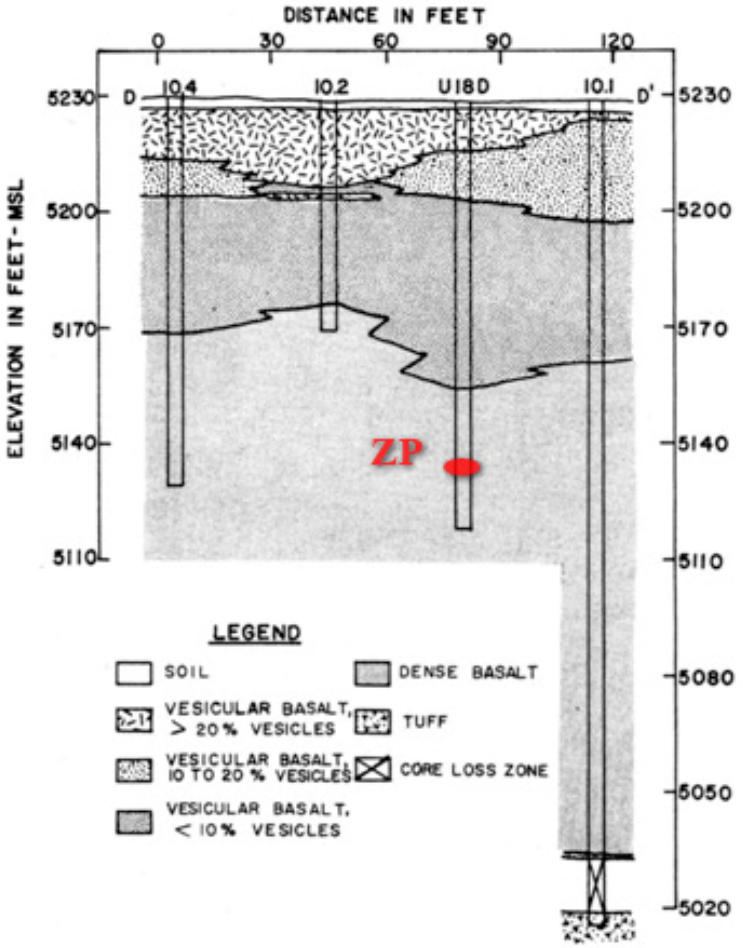
- **MOUND (AVG: RANGE):** RADIUS = 100: 80-130 FT, HEIGHT = 21: 15-26 FT, VOLUME = 30,000 FT^3, CONTINUOUS EJECTA = 80: 72-87 FT, MAXIMUM EJECTA = 120 FT, SURFACE DISTURBANCE = 200: 175-215 FT
- **CENTRAL PIT (AVG: RANGE):** RADIUS = 29: 25-33 FT, DEPTH = 12 FT, ELEVATION = 9 FT, VOLUME = 6,500 FT^3
- **TECHNICAL DIRECTOR:** E.H. FLEMING
- **ORIGINAL CRATER AND EJECTA PROJECT:** NCG AND WES
- **REINVESTIGATION:** DNA/AFWL/USGS; R.W. HENNY AND D.J. RODDY PRINCIPAL INVESTIGATORS

SULKY

LOCATION MAP & GEOLOGY

[NUGENT, PNE-719, 1965, P. 22 & 26; ANNOTATED]



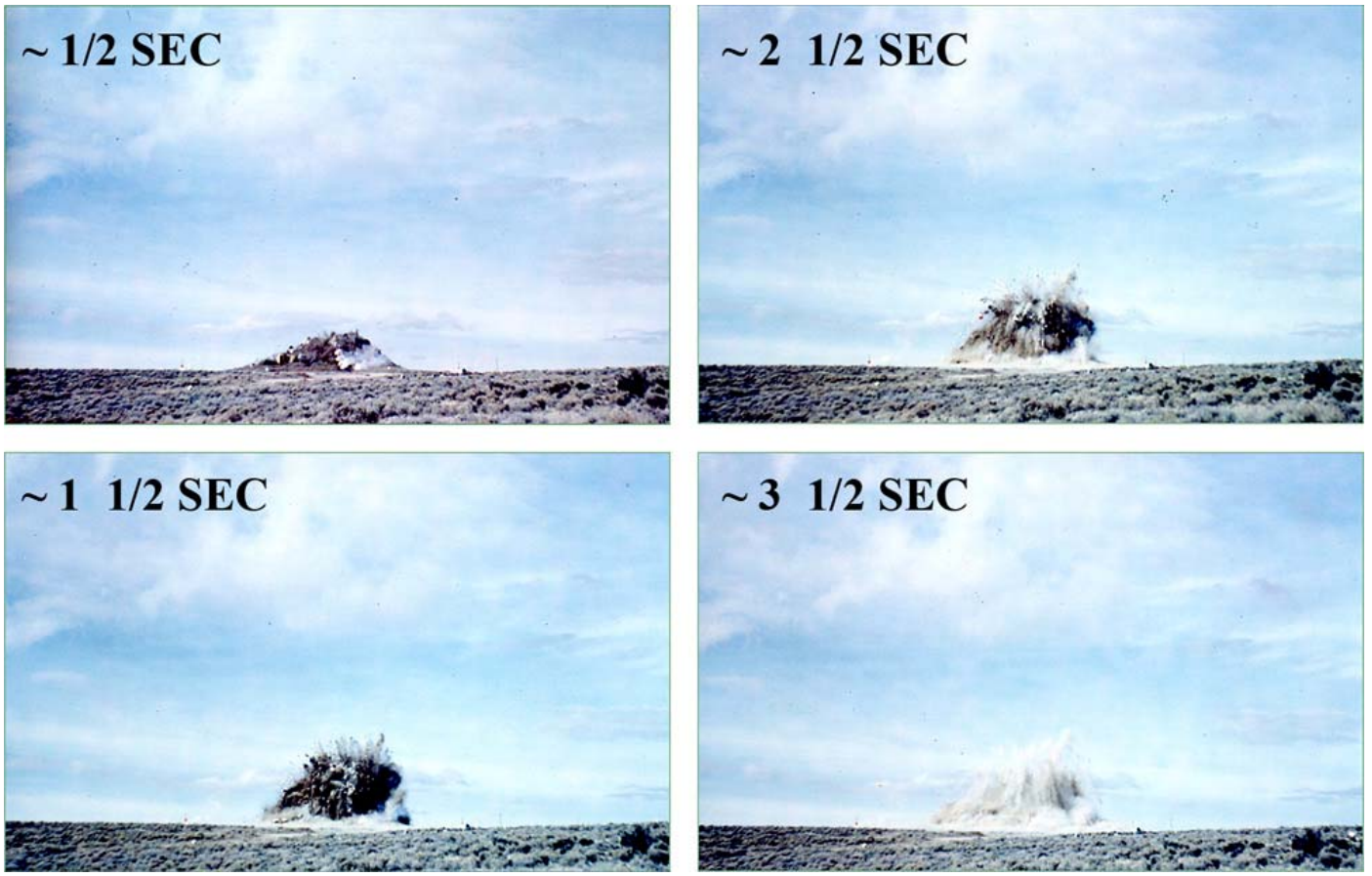


SULKY

DETONATION SEQUENCE

[LNLL (LRL) ARCHIVES; ANNOTATED]

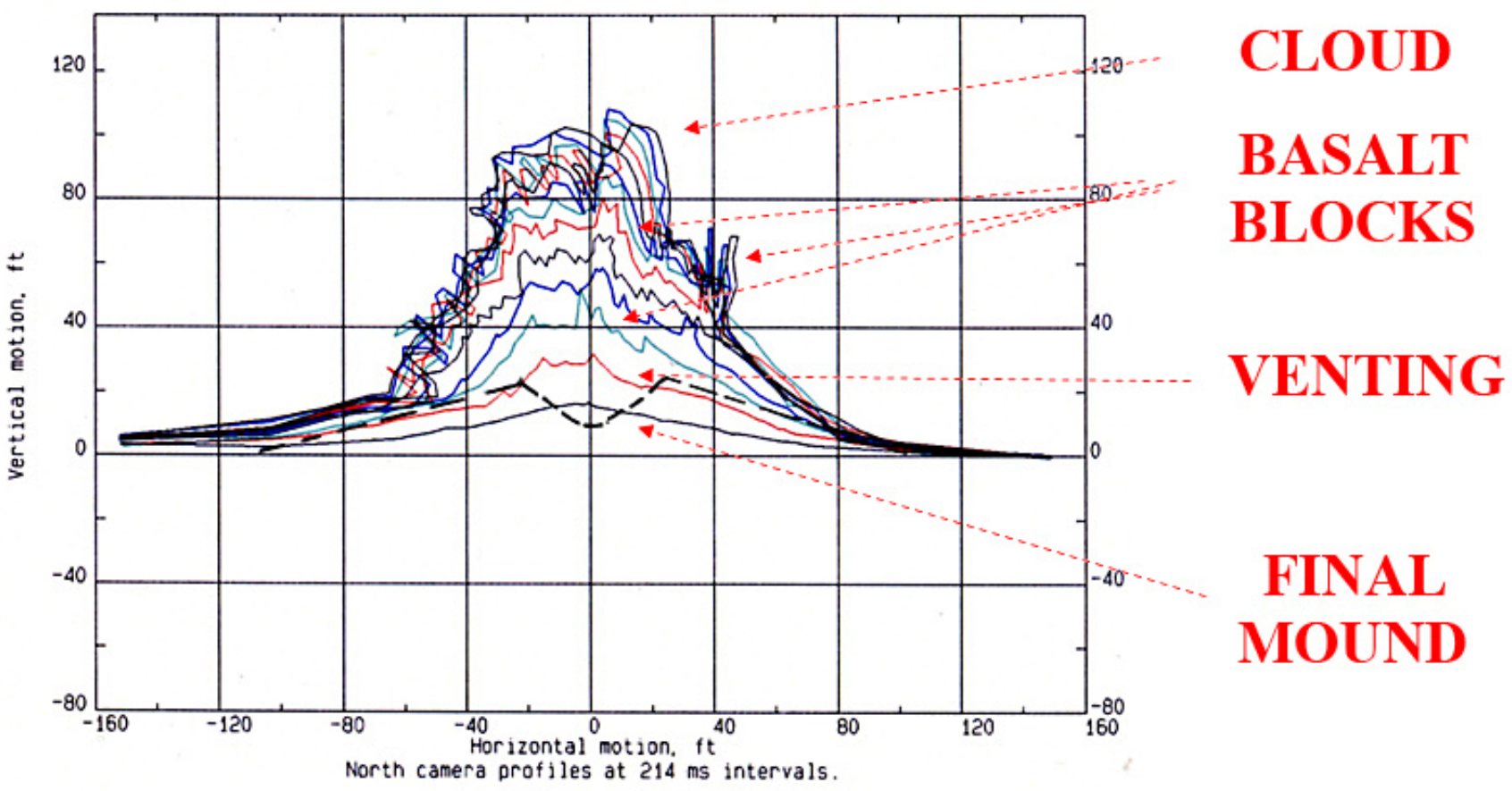
BASALT BLOCKS & TRAILING SOIL STREAMERS EJECTING NEAR VERTICALLY
FROM CENTER OF MOUND; TIMES ESTIMATED FROM BAIR, 1990



SULKY

VENTING HISTORY USING CINEMA

[BAIR, NMERI TECH NOTE, 1990; ANNOTATED]

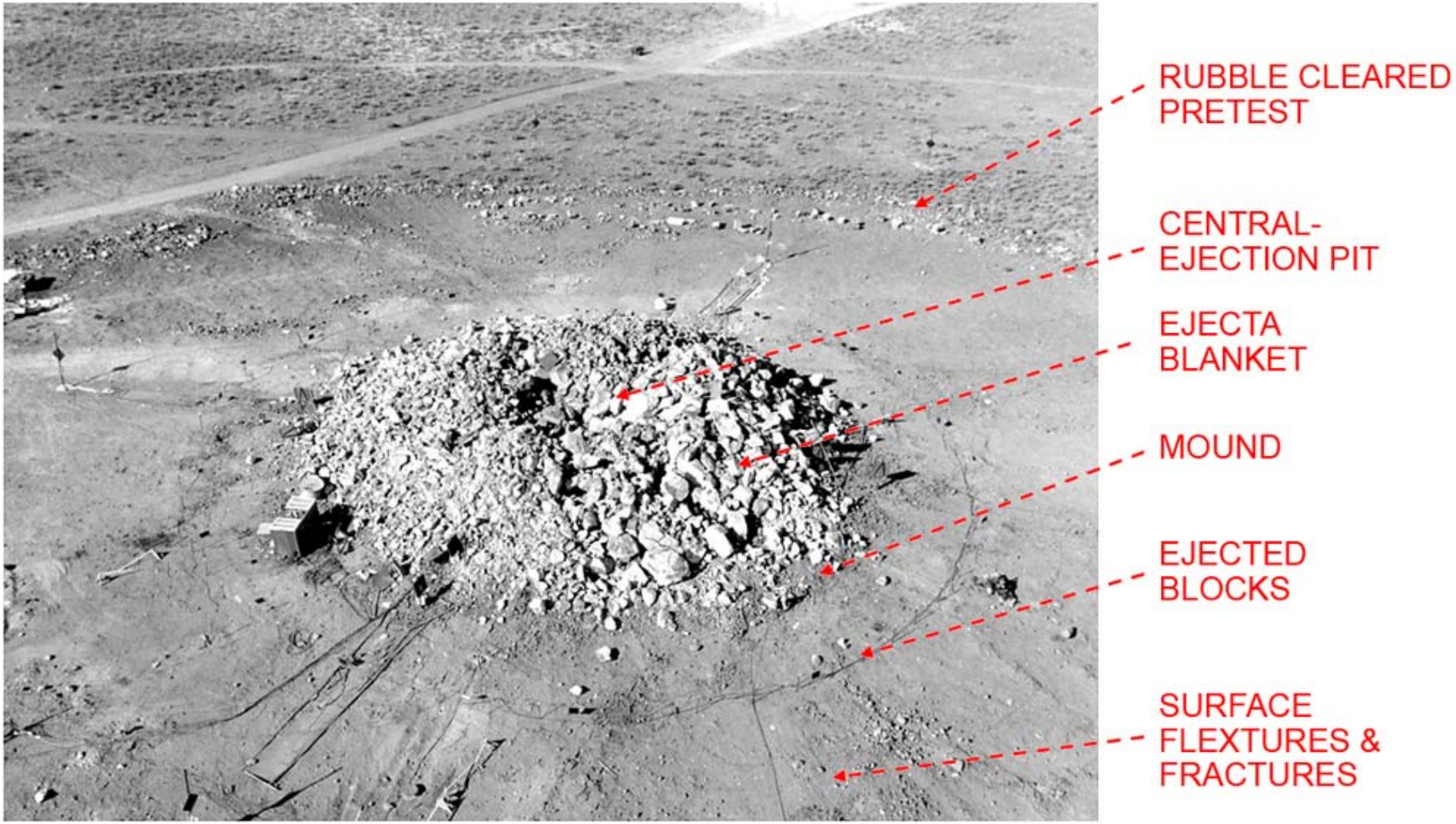


VENTING BEGAN ~ 400 MS WITH INDIVIDUAL BASALT BLOCKS EMERGING IN NEAR VERTICAL TRAJECTORIES, BY 1 SEC BASALT BLOCKS WERE BYPASSING DUST, BY 2 1/2 SEC THEY WERE FALLING WHILE DUST CONTINUED TO RISE FORMING THE CLOUD, LAST FRAME ANALYZED @ 2.782 SEC

SULKY

RETARC

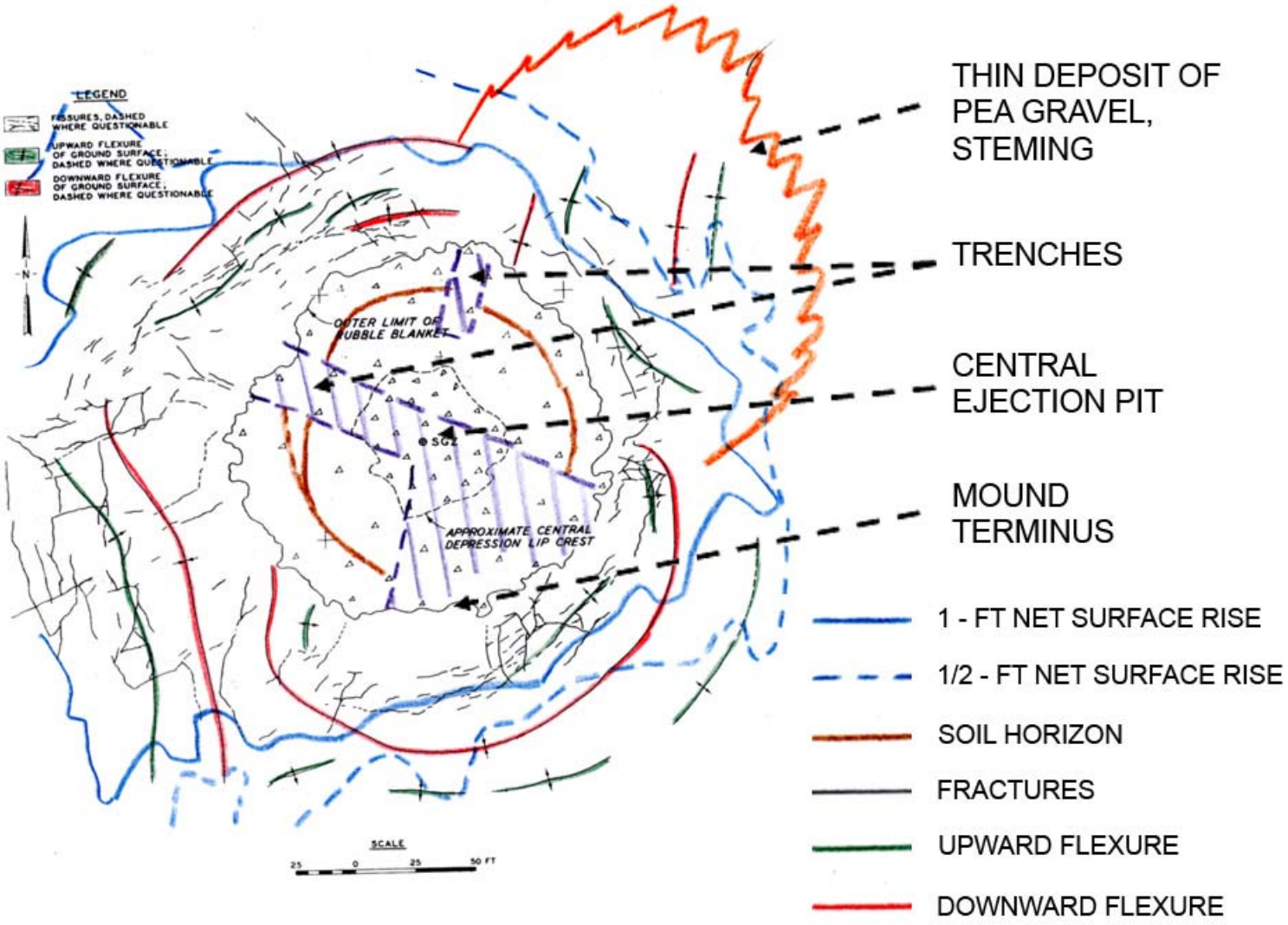
[VIDEON, PNE-713, 1965, P. 19; ANNOTATED]



SULKY

SURFACE FEATURES

[LUTTON, PNE-720, 1966, P. 74; MODIFIED]

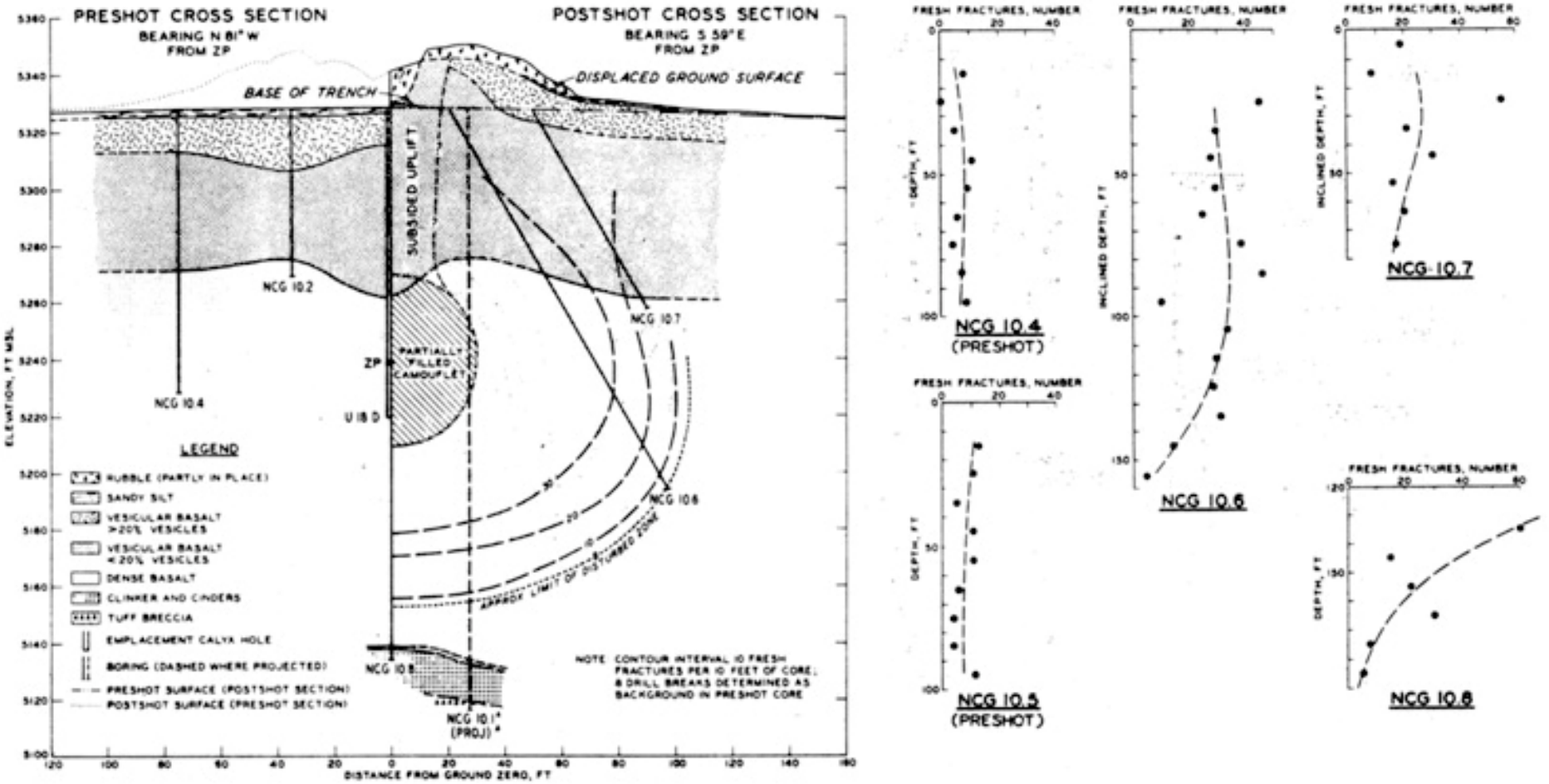


SULKY

POSTTEST CORING

[LUTTON, PNE-720, 1966, P. 75]

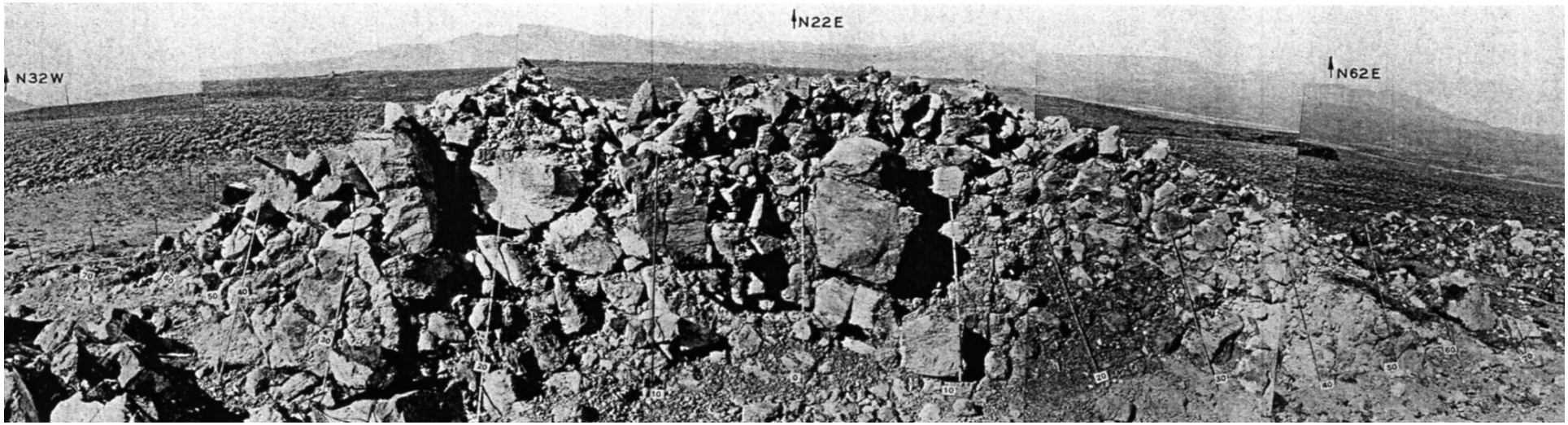
DEFINITION OF CAVITY AND BLAST-INDUCED FRACTURING



SULKY

TRENCH THROUGH RETARC

[LUTTON, PNE-720, 1966, P. 81-82]

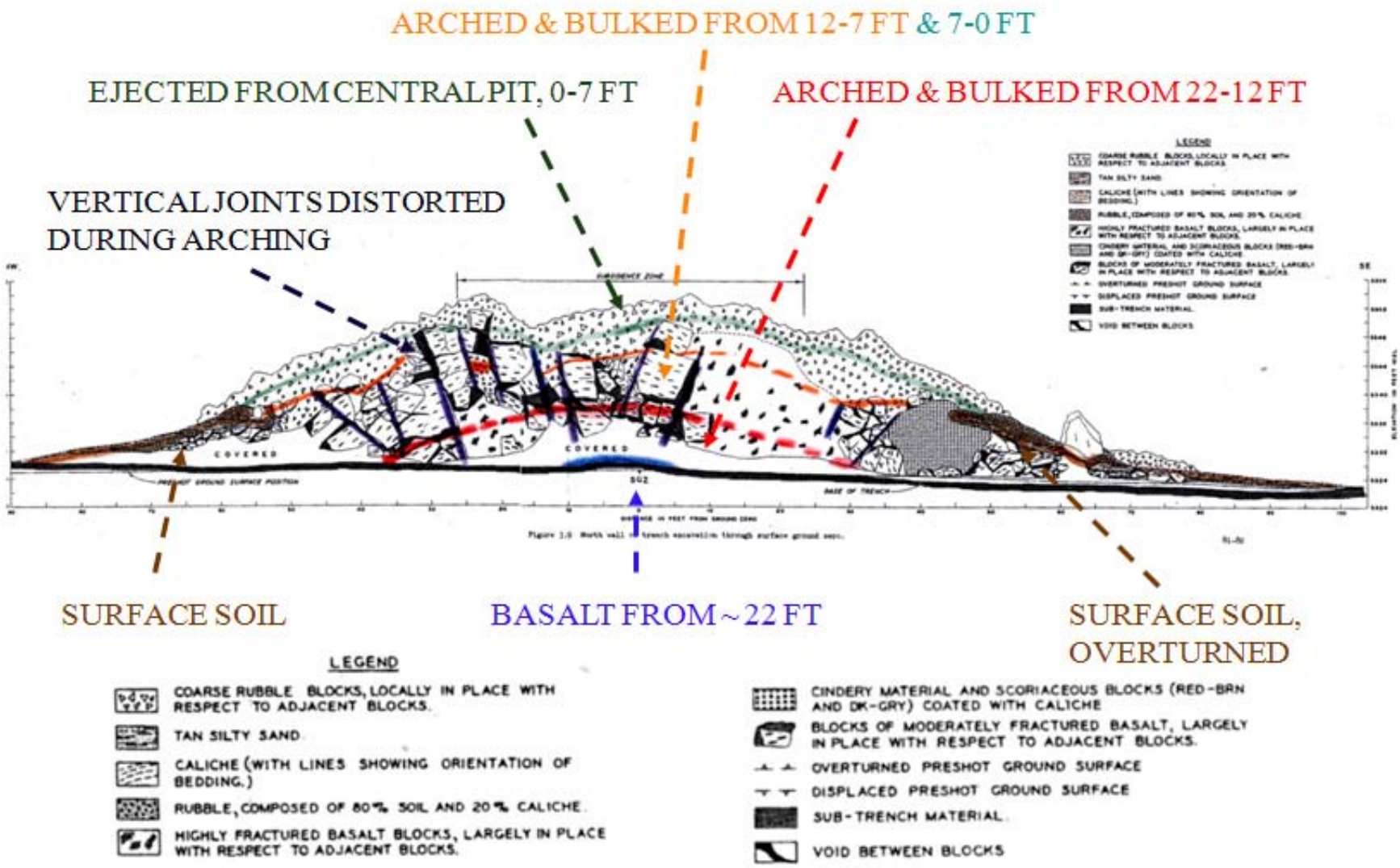


UPWARD ARCHED, BULKED AND “LOCKED” BASALT LAYERS OVERLAIN
BY 2 TO 4 FT OF BASALT BLOCKS EJECTED FROM THE CENTRAL - EJECTION PIT

SULKY

RETARC STRATIGRAPHY

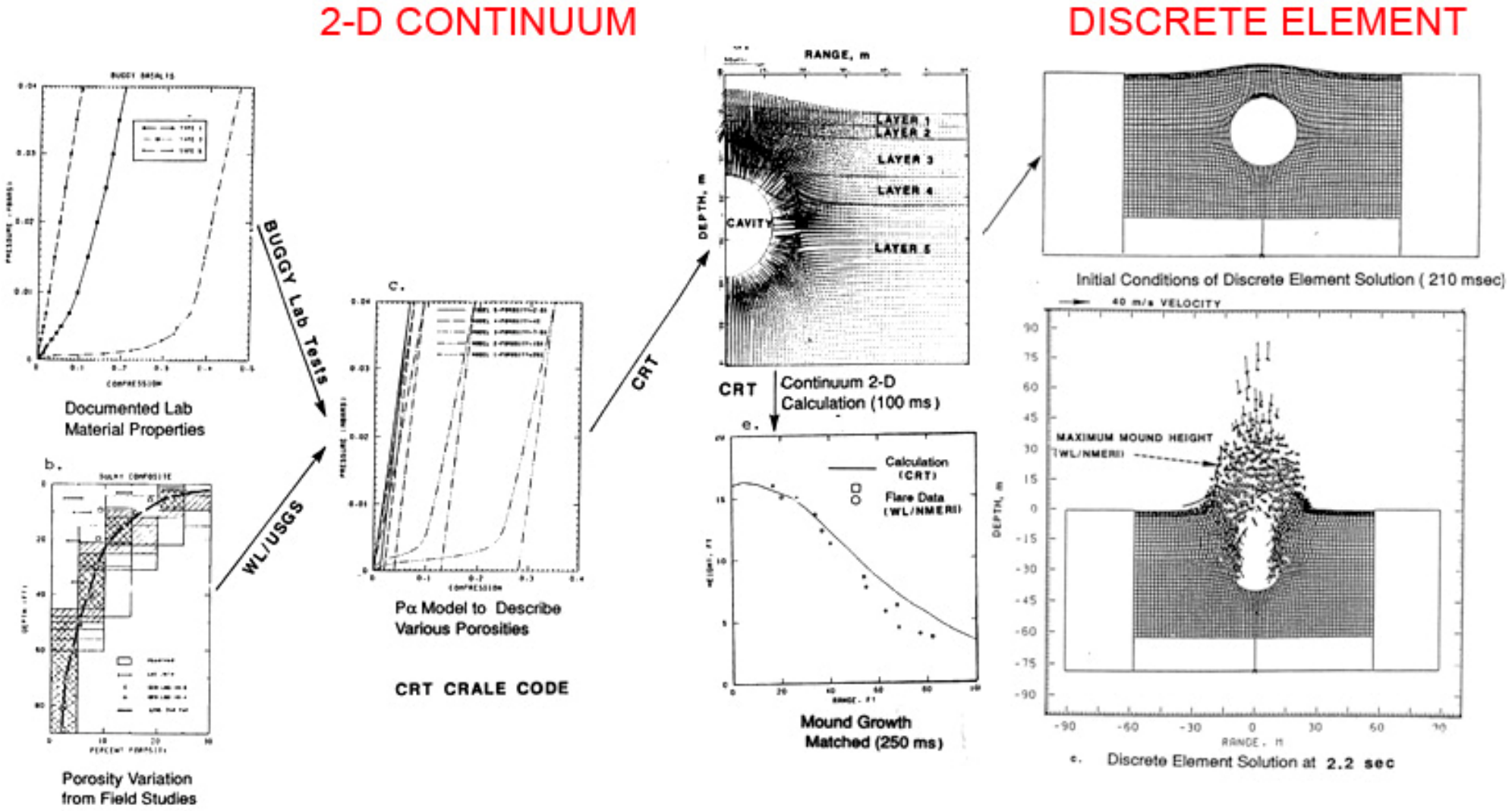
[LUTTON, PNE-720, 1966, P. 81-82; MODIFIED]



SULKY

CONTINUUM TO DISCRETE ELEMENT SIMULATION

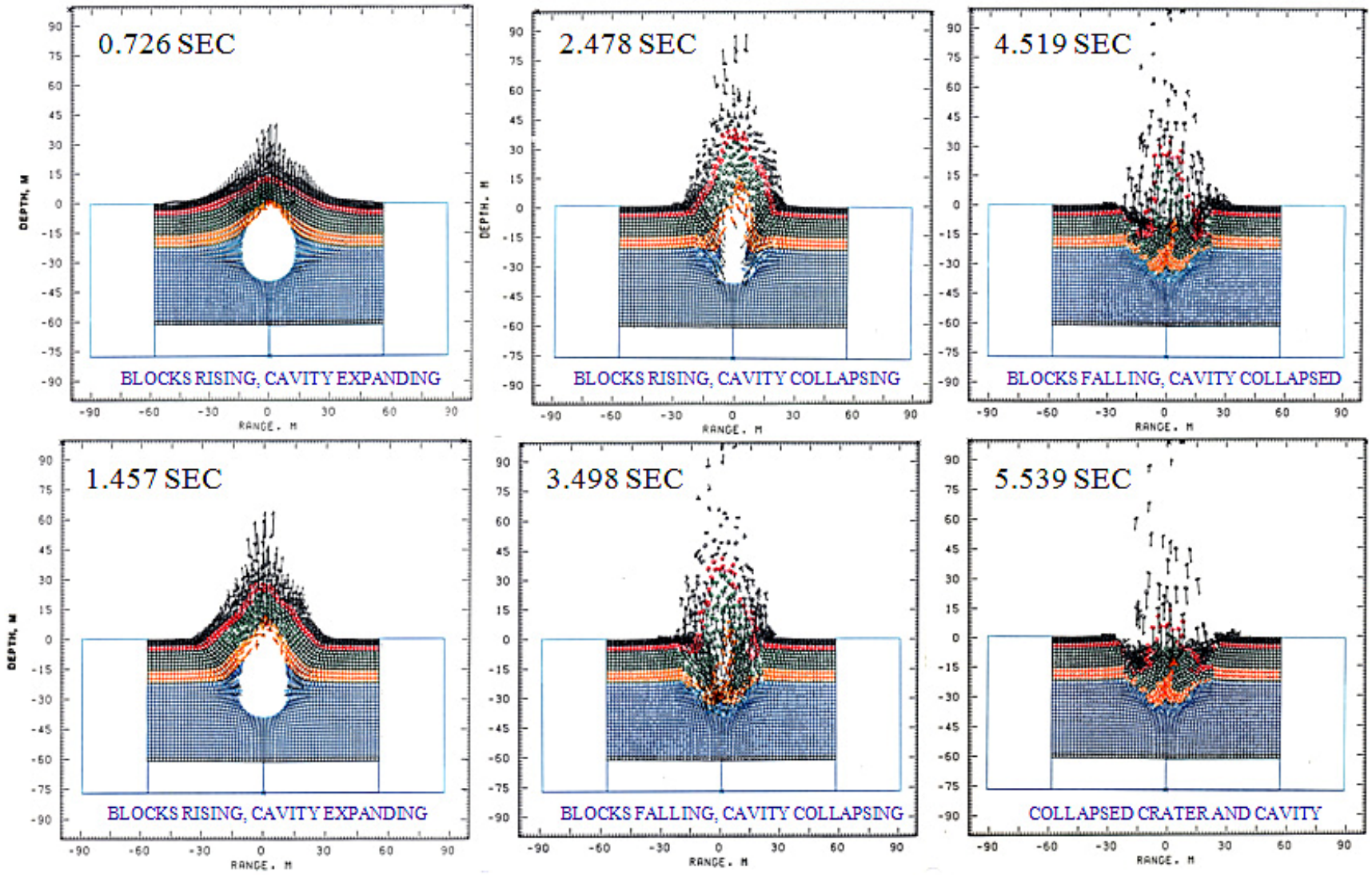
[ROCCO, DNA-TR-89-176, 1990]



SULKY

DISCRETE ELEMENT SIMULATION

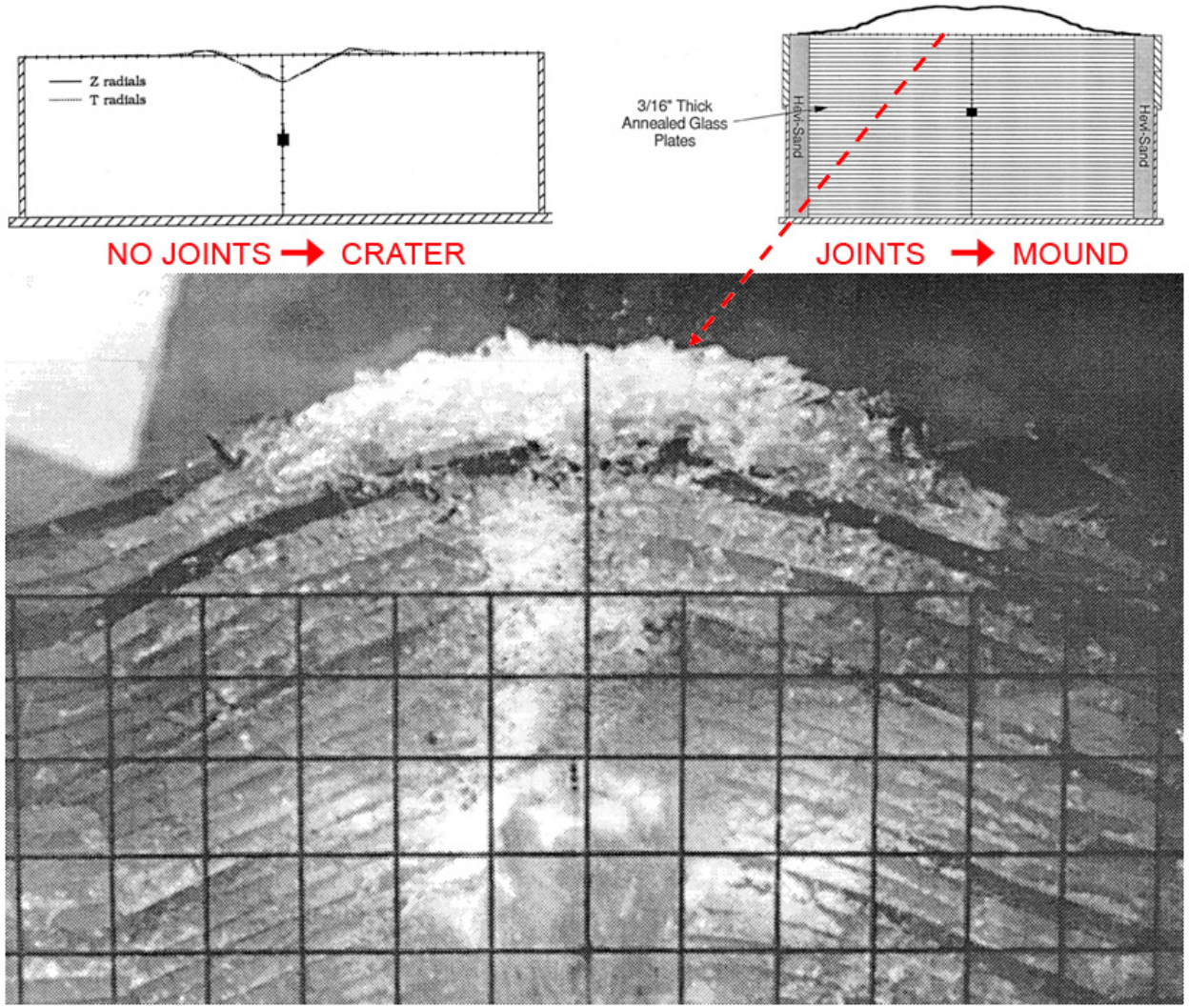
[THOMSEN, CRT-1289, 1991; ANNOTATED]



SULKY

CENTRIFUGE EXPERIMENTS

[HOUSEN AND SCHMIDT, DNA-TR-92-24, 1994; ANNOTATED]



SULKY

SUMMARY

- THE SULKY MOUND/VENT DEVELOPMENT WAS “MAPPED” FROM CINEMA TO 2.8 SECONDS AT WHICH TIME THE CLOUD WAS OVER 100 FT HIGH AND RISING, VENTING OCCURRED SHORTLY AFTER 400 MS, WHEN INDIVIDUAL BLOCKS EXITED FROM THE CENTRAL PORTION OF THE MOUND IN NEAR VERTICAL TRAJECTORIES, AFTER 2 1/2 SEC MOST OF THE BLOCKS WERE FALLING BACK TOWARD ORIGINAL GROUND SURFACE AND THE FINAL MOUND CONFIGURATION WHICH WAS CLOSE TO THE 400 MS MOUND LESS THE CENTRAL EJECTION PIT
- USING THE WELL EXPOSED STRATIGRAPHY IN THE 36-IN. CALYX CORE THE TRENCH THROUGH THE SULKY MOUND WAS MAPPED SHOWING A 2 TO 4 FT THICK BLANKET OF BASALT BLOCKS ORGINATING FROM THE SURFACE TO A DEPTH OF 7 FT UNDERLAIN BY IN-PLACE BASALT LAYERS ARCHED UPWARDS WITH INDIVIDUAL BLOCK SETS REMAINING TOGETHER BUT WITH JOINTS OPENED; VERTICAL JOINTS WERE ROTATED OUTWARD REFLECTING THE ARCHING
- THE 2-D CONTINUUM SIMULATION EMPLOYED A SITE LAYERING BASED ON THE PREVIOUS GEOLOGIC WORK WITH MODIFICATIONS OF THE POROSITIES FROM RE-EVALUATION OF THE 36-IN. CALYX CORE; INCORPORATING A MATERIAL MODEL FOR EACH LAYER USING THE BUGGY EVENT DYNAMIC MATERIAL MODELS THE MEASURED PEAK SURFACE VELOCITY OF 26 M/SEC AND MOUND GROWTH TO 400 MS WERE REPLICATED AND USED AS INITIAL CONDITIONS FOR THE DISCRETE ELEMENT SIMULATION
- THE DISCRETE ELEMENT SIMULATION TRACKED BASALT BLOCKS FROM 210 MS WITH BLOCKS RISING UNTIL 2 1/2 SEC AND THEN FALLING BACK TO GROUND WITH NO ARCHING PRESERVED RESULTING IN A SHALLOW CRATER RATHER THAN A MOUND

SULKY

SUMMARY (Continued)

- THE CALCULATED CONTINUUM MOUND MOTIONS AGREED WITH THE CINEMA DATA AND INDICATE A NARROW CONE OF NEARLY VERTICAL LOFTED BASALT BLOCKS – LATE-TIME MOTIONS OF THE LOFTED BASALT BLOCKS IN THE DISCRETE ELEMENT SIMULATION WERE NEARLY STRAIGHT DOWN WITH MINIMAL MATERIAL EJECTED BEYOND THE FINAL MOUND
- THE INITIAL CENTRIFUGE EXPERIMENTS EMPLOYED SILICA AND BASALT SAND TO DEVELOP A SCALING FACTOR; BUT RESULTED IN CRATERS RATHER THAN A MOUND – THEN USING A LAYERED ANNEALED GLASS A MOUND HAVING QUALITATIVE ASPECTS OF THE SULKY MOUND WAS ACHIEVED

SULKY

CONCLUSIONS

- SULKY CAN BE “VIEWED” EITHER MORPHOLOGICALLY AS A MOUND WITH A CENTRAL PIT (Ra = 0 FT, Da = -9 FT) OR MECHANISTICALLY AS A MOUND WITH A CENTRAL CRATER (Ra = .8 Ral OR 23 FT, Da = .5 Ra OR 12 FT); EITHER SET OF NUMBERS EQUALLY WELL SATISFIES THE DOB CURVE FOR DRY ROCK
- AND THE DIFFERENCE BETWEEN THE SULKY “CRATER IN THE MOUND” AND A “CRATER IN THE GROUND” IS PROBABLY A MATTER OF A DECREASE IN DOB OF NOT MORE THAN 10 FT
- FURTHERMORE, THE SULKY “CRATER IN THE MOUND” WOULD PROBABLY BE SIGNIFICANTLY LARGER IF A GAS ACCELERATION PHASE WAS PRESENT DUE TO A HIGH WATER TABLE; IE. A SEA-LEVEL ENVIRONMENT, OR OTHER GEOLOGIES; IE. LIMESTONE OR SHALE RESULTING IN DIFFERENT MOUND/CRATER SIGNATURES
- CLOSE CORRELATION OF THE FIELD, MOUND AND TRENCH MAPPING DEMONSTRATED THAT THE SOURCE OF THE EJECTA BLANKET COVERING THE MOUND WAS THE CENTRAL PIT OR EJECTION PIT ALL PROVIDING AN EXCELLENT BENCHMARK FOR THE COMPUTER SIMULATIONS AND CENTRIFUGE EXPERIMENTS
- THE ABILITY OF THE 2-D CONTINUUM SIMULATION TO MATCH OBSERVABLES TO 400 MS DEMONSTRATES THAT THE BASIC LAYERING AND MATERIAL PROPERTIES AND THUS THE IMPEDANCE GRADIENT OF THE SULKY SITE WERE SUCESSFULLY MODELED AND SHOWED THAT THE SITE POROSITIES WERE IMPORTANT IN TURNING THE FLOW FIELD TOWARDS THE VERTICAL THUS INHIBITING THE FORMATION OF A CLASSICAL THROWOUT CRATER
- THE DISCRETE ELEMENT SIMULATION SHOWS PROMISE IN BETTER UNDERSTANDING INDIVIDUAL BLOCK MOTIONS; BUT REQUIRES A MORE REALISTIC PRETEST MODEL WITH PERHAPS LARGER BLOCKS AND/OR INTERLOCKING/FRICTION BLOCKS SO THAT THE ARCH BECOMES “LOCKED” AND DOES NOT COLLAPSE

SULKY

CONCLUSIONS (Continued)

- THE CENTRIFUGE EXPERIMENTS SHOW PROMISE IN SIMULATING SULKY; BUT MORE WORK IS REQUIRED IN PRETEST MODELING TOGETHER WITH DIAGNOSTICS OF THE PROCESSES
- TOGETHER THE SYNTHESIS OF ALL THESE EFFORTS PROVIDES A NEW DYNAMIC LINK TO BETTER UNDERSTANDING THE SULKY EVENT – BUT CLEARLY MORE WORK IS NEEDED – THE FUN HAS JUST BEGUN

SULKY

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